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6. AUTHOR(S)
Herman B. Urbach, Donald T. Knauss, Balfour L. Wallace, John H. Wasser, Michael R. Sexton, John Frese

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Surface Warfare Center, Carderock Division
Annapolis, MD 21402-5067

Environmental Protection Agency
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

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13. ABSTRACT *(Maximum 200 Words)*
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EPA studies show that two-cycle marine diesel configurations combining exhaust-gas recirculation, retardation of the timing of injection, intercooling, and an oxidation catalyst for combustion of particulates lower NOx-emission levels to 8.5 g/kWh. Water injection appears ineffective below water-fuel ratios of 0.4, and is not cost effective for achieving the required NOx emission objective, at least in two-cycle engines. The proposed diesel configuration eliminates any negative ship impact on the engine-room spaces from water-management systems and water logistics.
Contrastingly, water injection into the combustor of gas turbines is a state-of-the-art development, which may be a low-risk, low-cost option for reduction of gas-tiurbine emissions. It is anticipated that the required pure water would be obtained from water purification plants and stored supplies.

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The Reduction of NOx Emissions from Marine Power Plants[1]

Herman B. Urbach, Donald T. Knauss, John Emory, Balfour L. Wallace
Naval Surface Warfare Center, Carderock Division, Annapolis MD 21402-5067

John H. Wasser
Environmental Protection Agency, Air Pollution Prevention and Control Division, Research Triangle Park NC 27711

Michael R. Sexton
Mechanical Engineering Department, Virginia Military Institute, Lexington, VA 24450

John Frese
Seaworthy Systems Inc., PO Box 965, Essex CT 06426-0965

Abstract

The EPA has proposed a 9.2 g/kWh NOx limit for maritime diesel engines. Gas turbines, which are always cleaner burning, have escaped maritime NOx mandates at this time. However, in Europe, increasingly stricter exhaust emission limits for shipboard turbines near high-pollution ports undergo periodic review as, for example, Dutch and Danish mandates (1) for the North Sea. Anticipating these proposed mandates, the Navy has been directed by OPNAVINST 5090.1A to comply therewith.

EPA studies show that two-cycle marine diesel configurations combining exhaust-gas recirculation, retardation of the timing of injection, intercooling, and an oxidation catalyst for combustion of particulates lower NOx-emission levels to 8.5 g/kWh, which is below EPA mandates. Water injection appears ineffective below water-fuel ratios of 0.4, and is not cost effective for achieving the required NOx emission objective, at least in two-cycle engines. The proposed diesel configuration eliminates any negative ship impact on the engine-room spaces from water-management systems and water logistics. Moreover, for two-cycle engines, the proposed configuration appears to be cost-competitive.

Contrastingly, water injection into the combustor of gas turbines is a state-of-the-art development, which may be a low-risk, low-cost option for reduction of gas-turbine emissions. It is anticipated that the required pure water would be obtained from water purification plants and stored supplies.

Steady-state tests of a water-injected combustor (WIC) system in an LM2500 propulsion-engine facility have provided important baseline data for tests on the WIC controller's unique automatic mode. The automatic mode was expressly designed to deliver acceptable water rates even during the abrupt power excursions encountered in emergency maneuvers, including collision-avoidance crashback.

[1] This work was supported by the Strategic Environmental Research and Development Program (Project No CP042).

Tests of water-fog injection (WFI) into the compressor inlet of an LM2500 engine show that WFI reduces both NOx emissions and the compressor-discharge temperature, without loss of thermodynamic efficiency. The reduction of the compressor-discharge temperature is somewhat similar to the reduction produced by the high-cost intercooling systems of recuperated engines. Simulation studies of a WFI-recuperated-cycle hybrid engine indicate that power output and efficiency can be significantly boosted simultaneously with NOx reduction at competitive cost.

Introduction

The work described herein was supported by the Strategic Environmental Research and Development Program (SERDP) sponsors, under the Compliance Pillar of the program.

The International Maritime Organization (IMO) and the Environmental Protection Agency (EPA) have mandated limitations on the emissions of NOx from new ships passing through territorial waters. Strict enforcement will be imposed by the end of the decade. The Navy has been instructed by OPNAVINST 5090.1A to make a good-faith attempt to comply with these limits on emissions in order to avoid costly litigation. The proposed EPA NOx maritime limit for diesel engines is 9.2 g/kWh. Gas turbines, which are always cleaner burning, have escaped mandates at this time. However, increasingly stricter European emission limits on the effluent from shipboard turbines near high-pollution ports undergo periodic review, as for example, Dutch and Danish mandates for the North Sea (1).

Modification of shipboard diesel engines to reduce NOx emissions with exhaust-gas recirculation (EGR), retardation of injection timing (RT), and intercooling (INTC) was explored at EPA facilities. Simultaneous injection of water fractions up to 40% to suppress NOx emissions were investigated.

Water injection into the combustors of gas turbines is a state-of-the-art development, which appear to be low-risk, low-cost option for the reduction of power-plant emissions. The retrofit of existing Navy LM2500 engines with the liquid-fuel version of the dry low-NOx combustors will require a factory replacement of the engine-combustor section. As a result, should the emissions mandates be invoked, retrofitting LM2500 engines with a WIC system would be less costly.

Initial tests of the WIC system with an LM2500 engine were conducted at the land-based engineering site at the Naval Surface Warfare Center, Carderock Division (NSWCCD) in Philadelphia. Steady-state operational data showing reductions of NOx emissions from the engine by both manual and automatic control systems are reported. Possible water-management systems for supplying the highly purified water are investigated.

As stated above, water-injection into the combustors of gas turbines can substantially reduce the emission of NOx. However, since the WIC system reduces turbine inlet temperature, the reduction of emissions is associated with a reduction in overall thermodynamic efficiency. In contrast, since WFI into a compressor inlet reduces the compressor-discharge temperature, it should also reduce compressor work, so that thermodynamic efficiency is enhanced. WFI tests on the LM2500 engine were conducted to quantify these effects on both the efficiency and NOx emissions. Tests of the application of a WFI system on the LM2500 compressor, indicating that it can reduce NOx emissions without loss of thermodynamic efficiency, are reported. The amount of purified WFI water required to achieve the mandated emission limit in the unique naval environment are discussed below.

The aforementioned WFI tests showed reductions in NOx emission as well as reductions in the compressor-discharge temperature, which approaches that of high-cost intercooling systems in recuperated engines. This reduction in compressor-discharge temperature, particularly as it relates to the application of WFI in recuperated cycles, was examined through WFI simulation studies, described in more detail below. These simulation studies of WFI application to simple and recuperated gas-turbine systems explore the potential of WFI engines for achieving significant increases in power output and efficiency simultaneously with ecological remediation at modest cost.

Suppression of NOx Emissions from Diesel Engines

The Navy inventory of maritime diesel engines consists of about 1400 units covering a wide power range. Diesel configurations include many versions of two-stroke and four-stroke cycle engines, with and without turbochargers. Thus, the retrofit of NOx-reducing devices is complex, and the retrofit options are numerous. Because of its frequent use in Navy applications, the DDC 4-71 two-stroke-cycle diesel was selected for evaluation of retrofit techniques. The proposed diesel configuration that evolved in this study is illustrated in Figure 1. It consists of an external EGR system with a filter and EGR control valve for varying the injection of exhaust gases into the inlet air flow. The percentage of EGR may be controlled by both the EGR control valve and/or the air control (throttling) valve. The recirculated gases reduce the combustion temperature, which lowers NOx formation. The intercooler (INTC) in Figure 1 is a water-cooled heat exchanger inserted between the turbocharger and the cylinders. The removal of heat from the mixture of air and combustion products reduces compression work and again lowers the combustion temperature. The blower provides positive scavenging of the diesel cylinders.

All the laboratory results reported at this point were obtained with a constant-speed engine driving an electric generator. Retarding the time of injection by 6.9 degrees closer to top dead center reduced NOx 37% with only a small increase in fuel consumption (See Table 1). With the addition of 10% EGR, NOx emission fell to 12.65 g/kWh, an overall reduction of 53%. Unfortunately, the levels of carbon monoxide (CO) and particulate matter (PM) exceeded the proposed standards. The increase in fuel consumption was too small for accurate measurement over a one-hour time interval.

To repress the CO and PM levels, an oxidation catalyst (OXC) was added immediately downstream of the turbocharger exhaust, which lowered CO levels below the proposed standards, and 90% below the baseline. Since the oxidation catalyst causes some back pressure and reduces noise, removal of the engine muffler increased efficiency somewhat, with little increase in noise level.

The oxidation catalyst induces combustion of the particulates, which permits, together with throttling of the inlet, an EGR increase from 10% to 16%. The output power is depressed 3.7% from the nominal 135-kW baseline power. (Rather than throttling the inlet air, EGR may be also be increased by enlarging the bypass valve to eliminate the throttle loss.) Fortunately, the combination of these systems with 16% EGR lowers the NOx level from the baseline 26.6 g/kWh to 8.5 g/kWh. Attempts to achieve further reductions in NOx emission through the use of emulsified fuel-water mixtures were based on previous positive experience with four-stroke engines. However, with the two-stroke engine, over 30% water had to be added before any NOx reduction was measured. Even then, only small decreases in NOx were observed as the water content was increased to 40%. A summary of the results of the diesel study is listed in Table 1.

The reduction in NOx, normally expected during water injection (2,3), did not occur in the above tests. The fact that water injection is unnecessary will have positive impact on the Navy shipboard applications,

the Navy shipboard applications, because the logistics of water supply and the mechanical injection equipment elevate costs. Therefore, water injection does not appear to be a viable, cost-competitive technology, at least for this class of two-stroke engines. At the present time, it is emphasized that the significant positive results described herein are attributes only of two-stroke engines at constant speed.

Based on the results in Table 1, it appears that NOx standards proposed by both IMO and the EPA can be met by most diesel-engine generator sets, without incurring the costs of water supply logistics. Moreover, if a 16% EGR level can be attained by increasing the size of the EGR valve, rather than by throttling the air inlet, the impairment of power and efficiency may be avoided. Dynamometer testing will be performed to ascertain that these conclusions apply to propulsion diesel engines.

Suppression of NOx Emissions from Gas Turbines

Background. The proposed limits on NOx emissions vary from state to state and depend upon the geographical location of the coastal area. At the present time, the only maritime restrictions for gas turbines are in the Dutch-and-Danish North Sea areas where oil drilling takes place (2). Around the early part of the decade, the Southern California Air Quality District proposed reduction of NOx emissions from marine gas-turbines below 42 parts per million (ppm). Other less restrictive proposals suggested a NOx-emission target of 60 ppm. Should the proposals be adopted, it would affect a Navy inventory of gas turbines including LM2500 engines for propulsion and 501K engines for ship's service power, totaling about 700 units. In response to this possible requirement and OPNAVINST 5090.1A, it was decided to examine the application of the WIC concept to Navy engines. Should the proposed emission targets be mandated, the Navy would have an available low-cost retrofit technology for compliance therewith.

Approach. Water injection into a combustor flame reduces NOx emissions arising from the Zeldovitch mechanism by lowering the flame temperature. The water-fuel ratio required to reduce emission of NOx below 40 to 60 ppm has been studied by the original equipment manufacturer (OEM). The General Electric (GE) Company (4) has suggested optimum water-fuel ratios varying from about 0.15 near the idle condition to a maximum ratio of 0.88 at full throttle. The water-fuel ratio falls as the engine power falls, due to the reduction of the combustor flame temperature. Controlling the water-fuel ratio in accordance with the above schedule would be satisfactory for most land applications. In fact, the suggested water-fuel ratio is often exceeded in order to produce more power, albeit at lower efficiency. However, the Navy gas-turbine requirement is more stringent because of the limited availability of high-purity water at sea. In addition, the system must be dependable during a crashback maneuver. This is a rapid (of the order of several seconds) gas-turbine deceleration to idle, followed by rapid gas-turbine acceleration to full reverse ship speed through the use of reversible pitch propellers. The crashback maneuver, must not subject the ship to an unscheduled loss of power during tactical encounters, or in crowded commercial sea lanes.

Description of the Proposed WIC System and Controller for Gas Turbines

As a consequence of these special requirements, it was necessary to design a WIC controller and manifold system that would protect the engine from unscheduled loss of power or engine damage during any fast deceleration. A low-cost WIC system with the aforementioned desirable characteristics would be quite successful and applicable to commercial maritime applications. A schematic diagram of the mechanical layout of the WIC system and controller is shown in Figure 2.

Fuel flow, measured by a fuel-flow meter in the fuel-supply line, is transmitted as an analog current signal to a programmable logic controller (PLC), which determines the rate of water injection. The PLC computes the required water flow from the fuel flow, and the ambient temperature and humidity. Also, the PLC utilizes the gas-generator speed to activate water delivery just above idle speed. The computed output signal from the PLC is fed to a solid-state, variable-frequency, variable-voltage, three-phase driver, which supplies variable-voltage electrical power to a variable-speed, three-phase electric motor. The motor drives a five-piston diaphragm, constant-displacement pump, which pumps water to the fuel manifold in direct proportion to the motor speed. The water flow rate is monitored by a turbine flow meter that transmits an analog signal to a comparator in the PLC, which corrects the output analog signal.

The PLC, the driver, the motor and the pump can react to transients within 0.2 sec, which provides the short response time needed for the crashback maneuvers.

Steady-State Performance of the WIC System

The WIC system was tested at the DDG51 land-based engineering site in Philadelphia. The fuel manifold of the LM2500 engine is identical with the existing manifold employed by ships of the DDG51 class. A demineralized water manifold was connected to the fuel manifold, which supplies an emulsified mixture of fuel and water directly to both the core and outer (secondary) nozzles. Water-fuel ratios as high as 0.74, corresponding to 22,000 hp, demonstrated NOx reduction below 55 ppm for both the manual mode and automatic mode of WIC system operation. NOx-emissions reductions are approximately proportional to the water rate, in conformance with published data (4). The steady-state performance of the manual and automatic modes of the WIC system fulfill the original NOx-emissions criteria needed to qualify for transient operation. At this time, the unique features of the WIC system, including its transient behavior during crashback maneuvers, are under study.

WIC-System Water Management for Gas Turbines

The maximum recommended level of dissolved impurities for water injection into an LM2500 combustor is 2 ppm. Water of this purity may be obtained from distillation plants or multistage reverse osmosis plants (5,6). However, the production rate of purified water is limited by available facilities. The method of supplying water to a particular Navy ship class will depend upon the operating mission of the ship.

A Plan for Fast Traverse of the Coastal Zone: For the sake of discussion, it is assumed that the width of a hypothetical restricted maritime pollution zone is 50 nautical miles (proposed by California shipping interests). For a DDG51-class ship (destroyer), passing through the coastal zone of California or through the vicinity of Dutch and Danish ports (1), the traverse time is estimated to be 3.7 hr. The combined water requirement for two LM2500 engines (a minimum of two in crowded sea lanes), two 501K engines, and the ship hotel requirement is 6 long tons per hour (lt/hr), according to Table 2. Because the limited distillation rate of the DDG is only 2.5 lt/hr, the total water shortfall will be 13 lt, which may be acquired from 59 lt of water stored in the potable water storage tanks. The ship commander generally prefers to maintain the ship potable water tanks in a full condition for purposes of good seakeeping and readiness. The make-up time needed to replace the 13-lt shortfall in the tanks is 10.4 hr at half-water rations. If the ship is tied at a dock, its shortfall may be made up from at-port sources.

Proposed Plan for Permanent Operation in the Coastal Zone: Navy ships with a

continuing mission to operate in the coastal zone would not have the makeup time to rebuild their resources of purified water from either existing desalination plants or potable water tanks. It is proposed that such ships would relinquish a portion of their fuel storage spaces for storage of purified water. The water would initially be supplied in port by truck. During underway replenishment of fuel, tankers, which normally supply fuel, would also provide purified water. Should a tactical situation arise changing the nature of their mission, such ships would discharge their inventory of water to take on fuel.

Water-Fog Injection into the Compressor Inlet

Water-fog injection into the bell-mouth inlet of the LM2500 gas turbine was envisioned to be a low-cost, low-technology option for reducing NOx emissions. Moreover, it was anticipated that the engine would not incur the loss of efficiency observed during water injection into the combustor. Commercially available systems for pre-cooling the ambient air boost both power output and efficiency. Water-fog injection into the compressor inlet cools the inlet air and continues to cool the air through the initial compressor stages where isothermal compression may be somewhat approached.

Figure 3 illustrates the WFI hardware integrated into the Navy LM2500 engine facility in Philadelphia. The water spray system consisted of a Rochem GTE 'Fyrewash' system delivering 2 gallons per minute (gpm) and a Lechler multiple-cluster-nozzle system delivering 2.21 gpm. The nozzles were aligned to provide both radially inward and axial flow of the sprays, with a total of 4.21 gpm at a pressure of 100 psi. The maximum injected flow rate of demineralized water, stored in a 500 gal tank and pumped by a Grundfos Type CRN2-60 centrifugal pump, was 4.45 gpm at 115 psi. Total water flow was measured with a turbine flow meter. Chemical monitoring of NOx and other chemical species was performed with an ENERAC Model 2000 combustion analyzer. All NOx data were corrected to 15% oxygen.

Desirable droplet sizes, recommended by one contractor (7), average about 10 microns. Larger droplets cause unacceptable blade erosion, as is observed in saturated steam turbines. The 10-micron droplet range requires pressures of the order of 3000 psi, which were not available for the test. As a result, large droplets, subject to high centrifugal acceleration while turning, strike the compressor walls. Droplets may coalesce and transfer of water from the bulk fluid stream into other engine spaces may occur. Large droplets, surviving centrifugation and evaporation in the first-stage working fluid, evaporate in later stages of the compressor.

Figure 4 is a plot of NOx emissions from the test LM2500 engine versus power for the dry and WFI conditions. The addition of 4.45 gpm reduces NOx emissions approximately 33 ppm over the power range. For power less than 6500 hp, NOx emission levels fall below 42 ppm. A rough extrapolation of the data indicates that 33 gpm of water is needed to reduce emissions below 42 ppm at 25000 hp. A 33-gpm flow of water corresponds to a water-fuel ratio of 1.4, or 60% more water than is recommended by the OEM (4) for water injection into the combustor. The scarcity, aboard Navy ships, of highly purified water needed for NOx reduction makes water consumption a major factor in the choice of a retrofit condition. As a consequence, the salt-water marine applications of WFI are not appropriate at this time.

Figure 5 is a plot of compressor discharge temperature versus power for the dry and WFI conditions. The result indicates that the compressed gas entering the combustor is 20 to 90° F cooler with WFI. The cooling effect decreases with increasing power because the water-air ratio decreases with power (the water flow is constant). Also, the result indicates that the reduction of NOx produced by the Zeldovitch mechanism can be attributed to at least two factors; colder air going into the combustor, and the higher

heat capacity of humidified air. Since compression power is proportional to the increase in compressor enthalpy, Figure 5 also indicates that WFI reduces power requirements for compression. As a result, more power may be delivered to the shaft.

Figure 6 compares the WFI effect on the free-power turbine inlet temperature (FTIT) in the normal dry and wet condition. The temperature reduction varies inversely with power because the water-gas ratio varies inversely with power. However, at the idle condition, the data appear anomalous. The results in Figures 6 arise because of the normal operation of the fuel controller. The controller responds to power output, comparing delivered power to power demanded by the command control center. When, on application of WFI, too much power is delivered, the controller comparator commands a reduction in combustor fuel flow, which lowers the gas-generator turbine inlet temperature and the temperature at down-stream locations. At the idle condition, the comparator does not produce a reduction signal. Consequently, the reduction in FTIT should be negligible and the apparent anomaly at idle power in Figure 6 is quite normal.

Figure 7 is a plot of specific fuel consumption as a function of power. The data show that WFI does not improve the efficiency of the LM2500-engine configuration used in this study. In fact, the data show that there may be some slight reduction in performance around 5000 hp. However, the data around 2200 hp do not demonstrate this reduction. Also, some power and speed variance (scatter) may account for the data. It is concluded that the net anticipated gain in efficiency from WFI is negated by the reduction in turbine inlet temperature. The results observed in Figures 6 and 7 arise because of the normal operation of the controller.

Apparently, similar unpublished proprietary data (8), obtained by the OEM on similar engines, confirm the results reported above. The OEM concluded that the Navy's Woodward controller, which is designed to maintain a specific power demand, prevents the attainment of the theoretically predicted power enhancement. Short of changing the controller, they suggested using variable-area turbine inlet blades (VATN's), which would permit use of more power in other applications. VATN's would reduce gas flow and limit output power, which would lead to increased efficiency in the existing Navy application. The cost of a controller is of the order of $10 k to $40 k, whereas the development cost of VATN's would be of the order of $10,000 k.

The Scope of WFI Simulation Studies

The potential of WFI to yield enhanced power and efficiency appears to have interested some private-sector companies and the Electric Power Research Institute (EPRI) (7,9). Subsequent to completion of the WFI tests, NSWCCD learned that EPRI was supporting the development of WFI, which they call 'overspray.' EPRI has provided cost-sharing assistance to the Missouri Public Service (MPS) Company in adapting overspray to an electric power plant employing twenty FT4 gas turbines.

Several papers have discussed the ingestion of rain water into the compressor inlet of air-frame gas turbines (10) during heavy downpours. The particular concern in these cases is the danger of unscheduled engine flame-out. However, hazards arising from compressor surge, which can induce stall and flame-out are also serious concerns. After completing the simulation study, the writers learned of the existence of a NACA (11) simulation of jet engines (compression ratio of 4.61 with isentropic efficiencies of 0.8 and 0.85 for the compressor and turbine respectively), concerned with boost power for aircraft.

The application of the WFI concept to the entire domain of gas-turbines cycles appears useful, because it lowers the compression energy requirements. Its application to simple cycles in the EPRI-MPS plant proves its utility in simple-cycle applications. It is clear from the reduction in compressor discharge temperature in Figure 5 that the system may likewise be useful in recuperated cycles. The computer modeling described below was developed to investigate these possibilities.

Simulation of WFI Application to Simple Cycles

Simulation of water-droplet evaporation has thus far been based upon an instantaneous equilibration model. Other more-realistic evaporation-limited models, taking into account the finite rate of heat diffusion through the thermal boundary layers at the water-gas interface, are under study at this time.

The model assumes that bone-dry air enters into the compressor bell-mouth at 100° F. Following thermal equilibration with 85° F water, the cooled mixture traversing the first-stage stator blades consists of air and water droplets diminished by evaporation into water vapor. The final adiabatic temperature, and the partial pressures of the air and water vapor were calculated with accounting for pressure head loss due to the mixing process. The computational procedure for the entropy of the two-phase mixture from these data accounted for the loss of pressure.

The computer model accounts for parasitic energy consumption such as the desalination of salt water and from the pumping of water in its calculation of the overall thermodynamic efficiency. Table 3 lists some of the parameters employed for input operating conditions and loss coefficients. The compressor pressure ratio (PRC), mass flow and turbine inlet temperature employed in the simulations approximate some LM2500 characteristics, with power output at a nominal 25,000 hp. Isentropic component efficiencies for the compressor, gas-generator turbine and free-power turbine are identified by ETAC, ETACT and ETAPT. Inlet head loss and combustor loss coefficients are given by DLPIN and DLPB.

The schematic diagram of a gas turbine with WFI shown in Figure 8, differs from the simple-cycle engine only in water injection. Figure 9 is a graphical display of results of a computer simulation of the engine in Figure 8. It shows the reference baseline performance curve of the simulated engine without WFI. Superimposed on the baseline curve are performance curves for fixed air flows, but with increasing amounts of WFI. Following attainment of a peak of efficiency, the efficiency ultimately falls off below the baseline condition. Thus, the graphical data indicate that the optimum amount of water is quite small at low power and low air-flow rates, and rises with increasing power and air flow. Moreover, as water flow increases from vanishing flow rates to flow rates of the order of 24 gpm, both power and efficiency increase.

Figure 10 compares the performance of the 25,000 hp simple-cycle engine without WFI and with WFI at 10 gpm. The data of Figure 9 show that the WFI-curve of Figure 10 has not been optimized with respect to water addition. At low output powers, the desirable water rate should be less than 10 gpm, and more than 10 gpm at higher output powers. The data indicate a relative efficiency rise of the order of 7% near the high design power. At part load the relative rise in efficiency appears greater.

Figure 9 shows that power output may be boosted more than 25%, depending upon the surge-limited WFI rate. The simulated 25% power increase appears consistent with increases in the NACA (11) simulation of thrust augmentation for a lower-performance hypothetical jet engine. In the EPRI-MPS utility plant (7,9) a real WFI rate of only 6.2 gpm produces a 13% increase in power.

The actual magnitude of the power increment depends upon the amount of water that can be ingested into the compressor without inducing unacceptable surge. The calculated power enhancements are based on assuming that the surge-limiting WFI rate for the LM2500 is 24 gpm. The validity of this assumption is under study. However, for WFI, the implication of such a validation is that at many operating points, NOx emission levels would lie below EPA limits.

Table 4 lists the estimated costs of a simple-cycle engine equipped with WFI. The estimates for the single-spool gas generator may be obsolete, since they are based upon Navy costs for the stripped-down engine in an enclosure on a skid. The dollar value for the free-power turbine is based on the additional cost incurred by an uprated turbine developing considerably more power. However, whatever the underestimate of costs arising from inflation, the conclusion of our argument, namely that the WFI-simple-cycle engine is more cost-competitive, is still true. Higher estimates for the LM2500 would increase this cost-competitive advantage of WFI over the purely simple-cycle engine.

The net serendipitous result is that WFI-simple-cycle, gas-turbine engines incur simultaneously, reduction of NOx emissions and significant boosts in power output, overall thermodynamic efficiency and cost competitiveness.

Simulation of Recuperated Gas Turbines with WFI

The depression of the compressor discharge temperature, shown in Figure 5, was reproduced in the computer simulations. Reductions in the compressor discharge temperature, at the assumed surge-limiting 24-gpm flow, were over 230° F at design power and airflow. Thus, this reduction suggests utilizing WFI to perform the function of a conventional intercooler in recuperated gas turbines. Figure 11 illustrates the schematic diagram of such a recuperated gas turbine with WFI.

Figure 12 compares the computational results for the engine of Figure 11 with the simple-cycle result. The computational results of Figure 12 were not optimized for intermediate and low powers, where water injection rates should be reduced from the high-power water rates. Thus, at intermediate and low power, efficiency increases should be greater than indicated in Figure 12. Nevertheless, at full power, efficiency is boosted from 35% in the simple-cycle engine to 46% in the WFI-recuperated engine. Power output is increased 26%.

Water and Fuel Consumption Aspects of the Various WFI Engines

The estimated dedicated water requirements for a destroyer with four WFI-LM2500 engines (nominal output power of 100,000 hp) consuming purified water at the 10-gpm and 24-gpm rate are 17,3 00 and 41,500 gal/day. The nominal purified-water production capacity for new destroyers will be 24,000 gal/day from two 12,000 gal/day reverse osmosis (RO) plants. Only half the 24,000 gal/day capacity is actually used because one unit is a standby emergency plant. The purified water for WFI will employ three-stage RO units to reduce the total dissolved solids to less than 2 ppm.

The various WFI engines will have additional space and weight requirements for water-purification equipment in the engine room. The weight and volume statistics for a 17,300-gal/day RO desalination plant are estimated (based upon proportioning from the modular characteristics of RO units as in Reference 12) to be 3.8 lt and 797 cubic ft, according to Table 5. The increased space requirement, even for the 41,500-gal/day plant, should have little ship impact, because as shown in Table 6 below, there will be substantial weight and volume savings in fuel tankage.

Table 6 lists savings of yearly fuel, etc., for alternative cycles and selected WFI rates based upon the invariant ship range. Based on a typical power profile, estimates of the yearly fuel savings accruing to a DDG-class destroyer from a 100,000-hp WFI-gas-turbine power plant are shown in the third column of Table 6. The table shows fuel savings for WFI simple-cycle gas turbine engines (Figure 8) at 0.0, 10 and 24 gal/min, and fuel savings for WFI recuperated cycle engines (Figure 11) at 0.0, 10, and 24 gal/min. Since the water flows into the engines were not optimized for variation of the power, total fuel savings should be greater than the graph indicates. For example, in the simple cycle, a 24-gpm WFI rate saves only 2.76% fuel, which is less than the 3.5% fuel savings for the 10-gpm rate. The 20.59% fuel savings for the recuperated cycle with only a 10 gpm WFI rate would reduce the ship weight (13) by 244 lt and the ship volume by 9760 cubic ft, if the ship range were assumed to be invariant.

As a consequence of these fuel weight and volume savings, any negative impact, from the water-purification plant on Navy ship systems is likely to be small. Moreover, expenditures for the dedicated RO plant, estimated at $300 k (for the 17,300 gpm unit), are not likely to negate the cost-competitive advantage of WFI applications. Finally, the reduction of NOx emissions generated by WFI enhances significantly its potential application as a commercially viable, low-pollution power plant for the Navy.

Conclusions

The Navy has been increasingly subject to demands to decrease ecological pollution in maritime environments. In response to official directives, it has made progress in its mission to reduce NOx emissions from Navy shipboard power plants. Diesel configurations have been improved to the point where emissions from highly polluting units such as the DDC 4-71 two-stroke-cycle engine, employing simultaneously, 16% EGR, 6.9° TR, OXC, and INTC are lowered from 26.6 to 8.5 g/kWh, well within EPA mandates. The study proved that, for two-cycle engines, the injection of water-fuel emulsions into the diesel cylinder is neither effective nor cost-competitive. The new water-free configuration appears to be a viable cost-competitive technology for the retrofit of the Navy's inventory of two-cycle diesel engines.

The reduction of NOx emissions from gas turbines through the injection of water into the combustor has been standard practice in commercial electric utilities. The use of water injection into the combustor appears to be the most-cost effective approach to the retrofit of gas turbines in the Navy. The steady-state operational requirements for water injection in the Navy do not differ from the steady-state requirements of commercial practice. However, the WIC system is a fleet-oriented device designed for compatibility with rapid (less than one-and-one-half second) gas-turbine deceleration to idle, followed by rapid gas-turbine acceleration to full reverse ship speed through the use of reversible pitch propellers. This procedure, the crashback maneuver, must not subject the ship to an unscheduled loss of power during tactical encounters. Steady-state WIC-system tests have demonstrated satisfactory operation with reduction of NOx in proportion to the water-injection rate. Study of the transient behavior is underway.

The scarcity of pure water at sea dictates that schemes for conserving water be consistent with Navy practice. For ships making rapid traverse through coastal waters, it is planned to utilize reverse osmosis and/or distillation facilities. For ships operating in the coastal zone for extended periods of time, the required water will be stored in tanks sequestered from the fuel-storage system.

Although WIC systems reduce thermodynamic performance in proportion to the amount of water, the reduction is tolerated as a penalty for NOx depression. Contrastingly, WFI into the bell-mouth inlet of

compressors also depresses NOx emissions without loss of thermodynamic efficiency. However, the amount of water needed is over 60% more than that required for combustor injection. Therefore WFI into the compressor is not practical where the cost of additional water facilities is restrictive. However, for a system with diminished constraints on water production, WFI produces more power and yields at least an equal thermodynamic efficiency.

WFI lowers compressor discharge temperature and therefore the overall compressor work requirements. This reduced work requirement accounts for predicted increases in power output and efficiency expected for WFI. The reduced work suggests that the application of WFI to both simple and enhanced gas-turbine cycles should have generally positive effects, which have provoked the interest of the gas-turbine community.

Simulations of the performance of the WFI-simple-cycle gas-turbine engine indicate that boosts of 25% in power and 7% in efficiency may be achieved depending on the surge-margin limit. Simulations of the WFI-recuperated gas-turbine engine indicate a more than 25% increase in power with a 35% increase in efficiency. The WFI concept promises to reduce NOx emissions in any configuration of gas turbines without loss of efficiency. Moreover, the WFI-gas-turbine combinations show cost-competitive advantages over existing engines in the fleet.

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Tables

Table 1. A summary of exhaust emissions in g/kWh obtained with the DDC 71-4 two-stroke diesel engine at 100% (135 kW) load.

POLLUTANT SPECIES	BASELINE EMISSION g/kWh	TR* g/kWh	10% EGR & TR* g/kWh	10% EGR & TR* & OXC g/kWh	10% EGR & TR* & OXC & INTC g/kWh	16% EGR & TR* & OXC &INTC g/kWh
NOx	26.61	16.82	12.65	11.73	10.2	8.5
CO	2.68	5.95	15.79	0.25	0.3	0.3
PM	0.09	0.24	0.61	0.29	nm	nm

* 6.9° closer to top dead center
nm Not measured

Table 2. Water management plan for fast traverse of a DDG through the coastal zone.

Estimated traverse time	3.7 hr
Engine water requirement*	3.5 lt/hr
Ship hotel water requirement	2.5 lt/hr
Water distillation rate	2.5 lt/hr
Water shortfall rate	3.5 lt/hr
Total shortfall	13. lt
Make-up time @ half-water ration	10.4 hr

* Datum based on two engines at cruise speed

Table 3. Parameters employed in the computer simulation of WFI applications to gas turbines.

AIRFLOW	TIT	PRC	ETAC	ETACT	ETAPT	DLPIN	DLPB
131.15 lb/sec	2660° R	18.0	0.866	0.894	0.925	0.0075	0.052

Table 4. Cost estimates for a simple-cycle LM2500 gas turbine with WFI.

Hardware Component	$ k
Water-fog injection system	100
Water purification system	100
Single-spool gas generator	4500
Larger free-power turbine	500
Total estimated cost	$5200 k
Cost for the WFI-LM2500	$167/hp
Cost for the simple-cycle LM2500	$180/hp

Table 5. Estimated weight and size of dedicated alternative three-stage RO desalination plants for nominal 100,000-hp WFI-gas-turbine power plants.

Water Consumption Rate		Weight	Volume	Estimated Cost*
gpm	gal/day	lt	cf	$k
10	17,300	3.8	797	300
24	41,500	9.0	2900	710

lt = long ton; cf = cubic feet
* using proportional analysis on data from Reference 12

Table 6. Estimates of ship fuel weight and volume savings for alternative WFI gas-turbine power plants.

Engine Configuration	Water Rate	Fuel Saving	Weight Saving	Volume Saving
	gpm	%	lt	cf
Simple Cycle	00	0.0	00	00
Simple Cycle + WFI	10	3.5	42	1660
Simple Cycle + WFI	24	2.8	33	1300
Recuperated + WFI	00	8.8	106	4170
Recuperated + WFI	10	20.6	244	9760
Recuperated + WFI	24	28.7	312	12460

lt = long ton; cf = cubic feet

Figure 1. The proposed EPA diesel configuration meeting the EPA emissions standard.

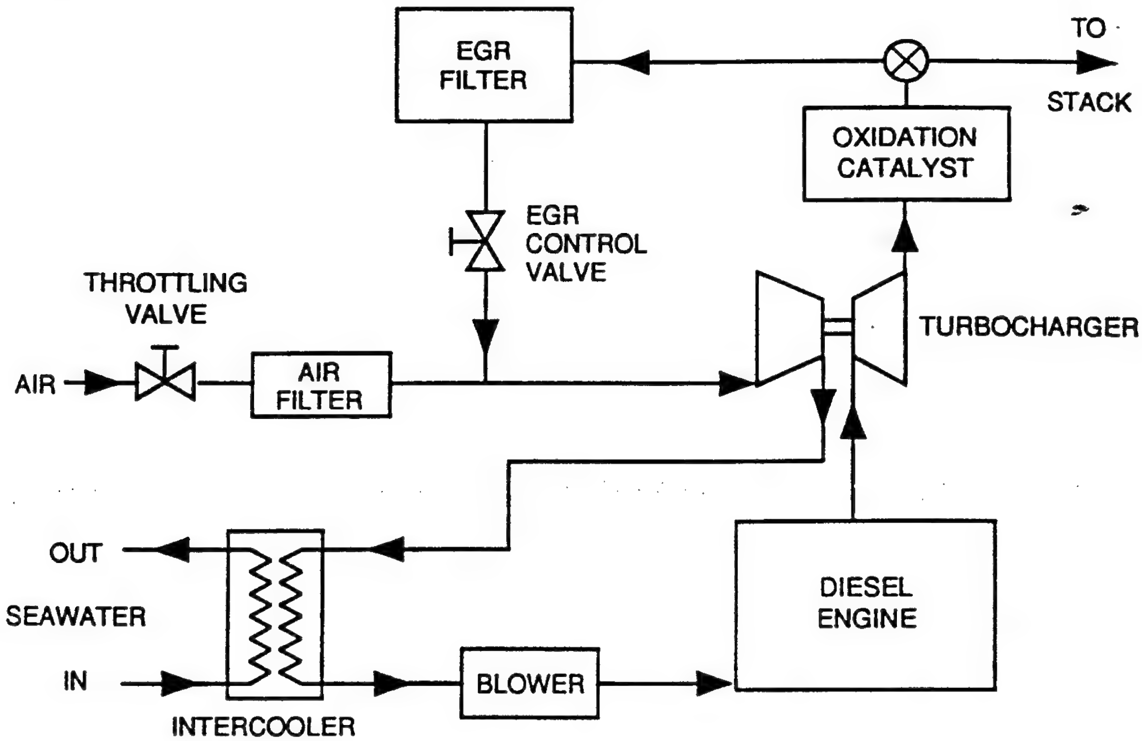

Figure 2. A schematic diagram of the electro-mechanical layout of the WIC system and controller.

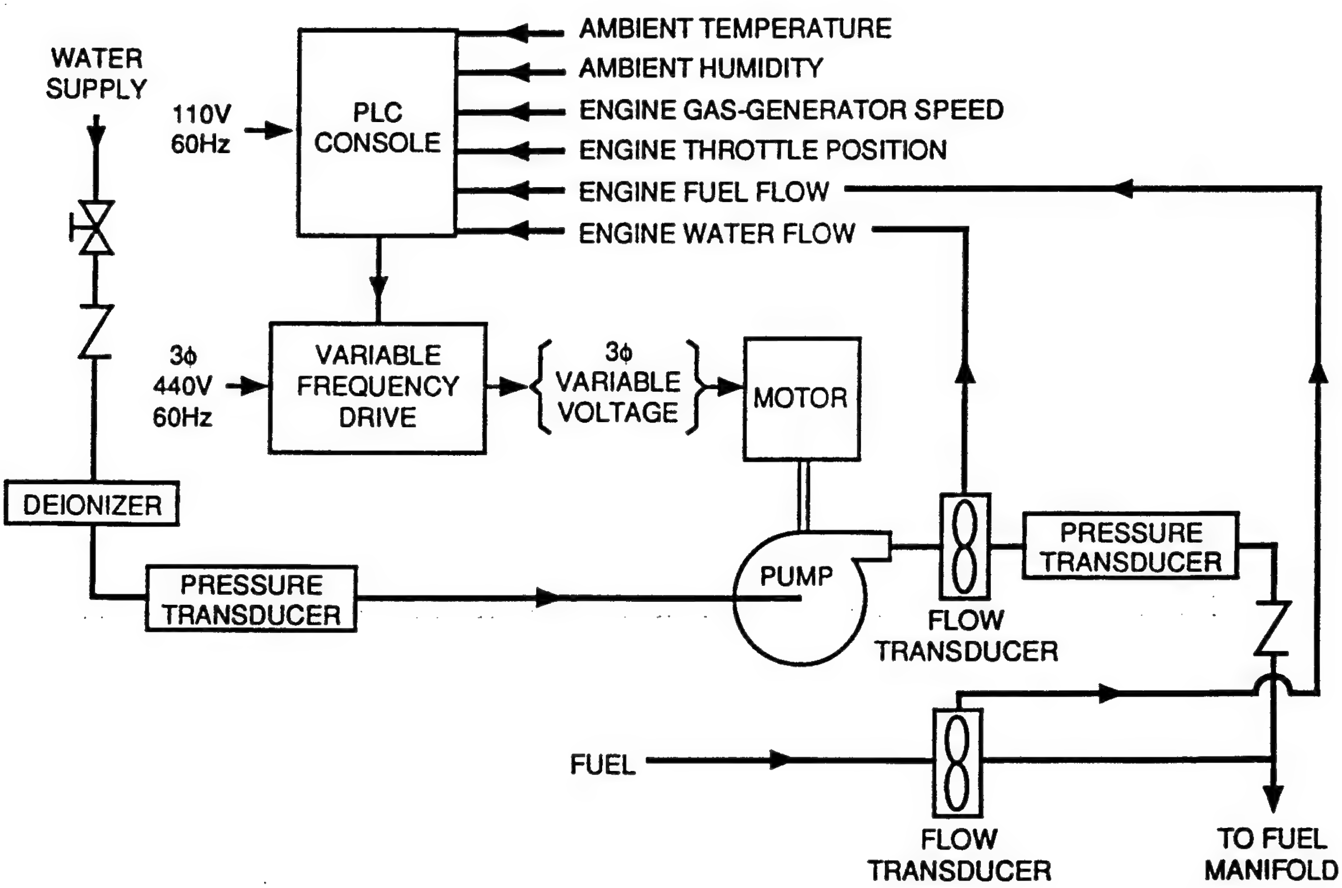

Figure 3. The water-fog injection system used in the LM2500 WFI tests.

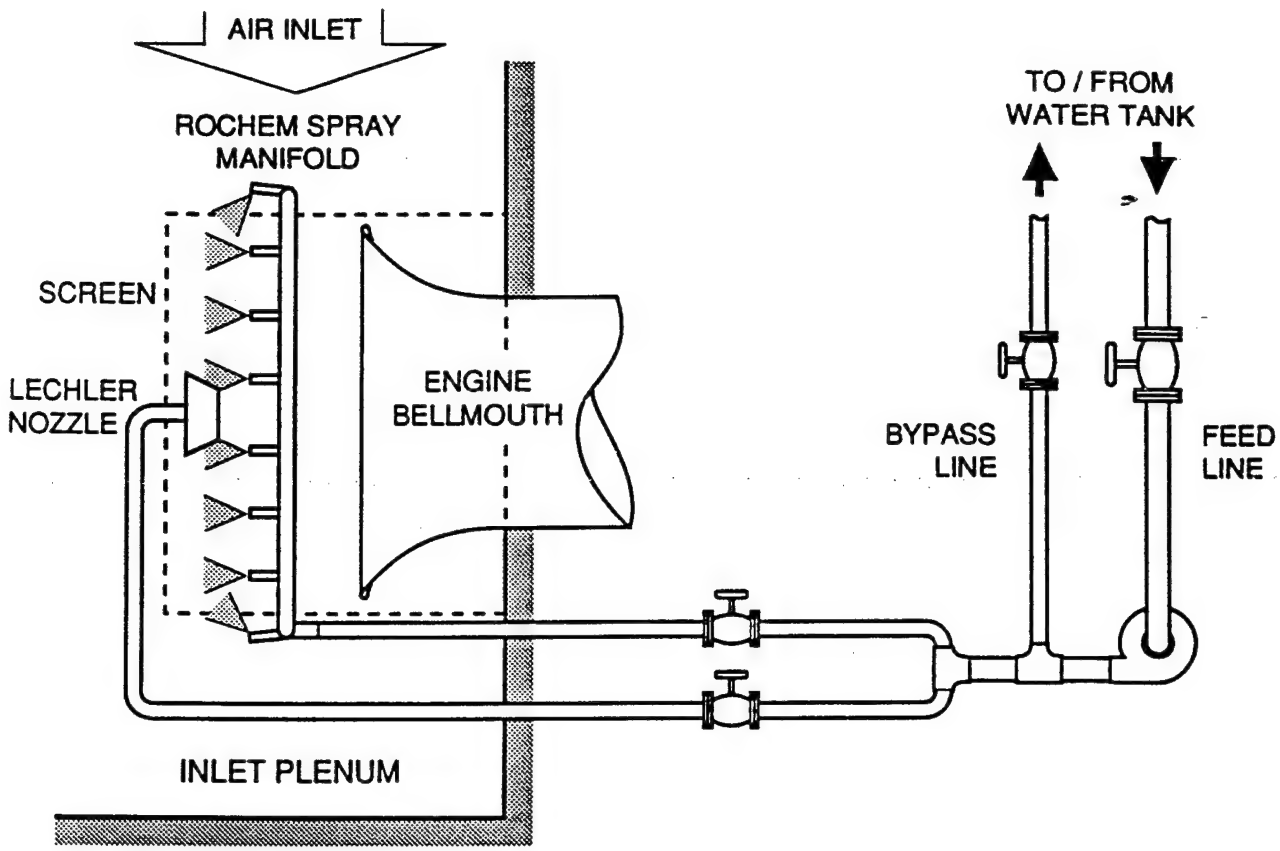

Figure 4. The effect of WFI on the emission of NO_X from the LM2500 gas turbine

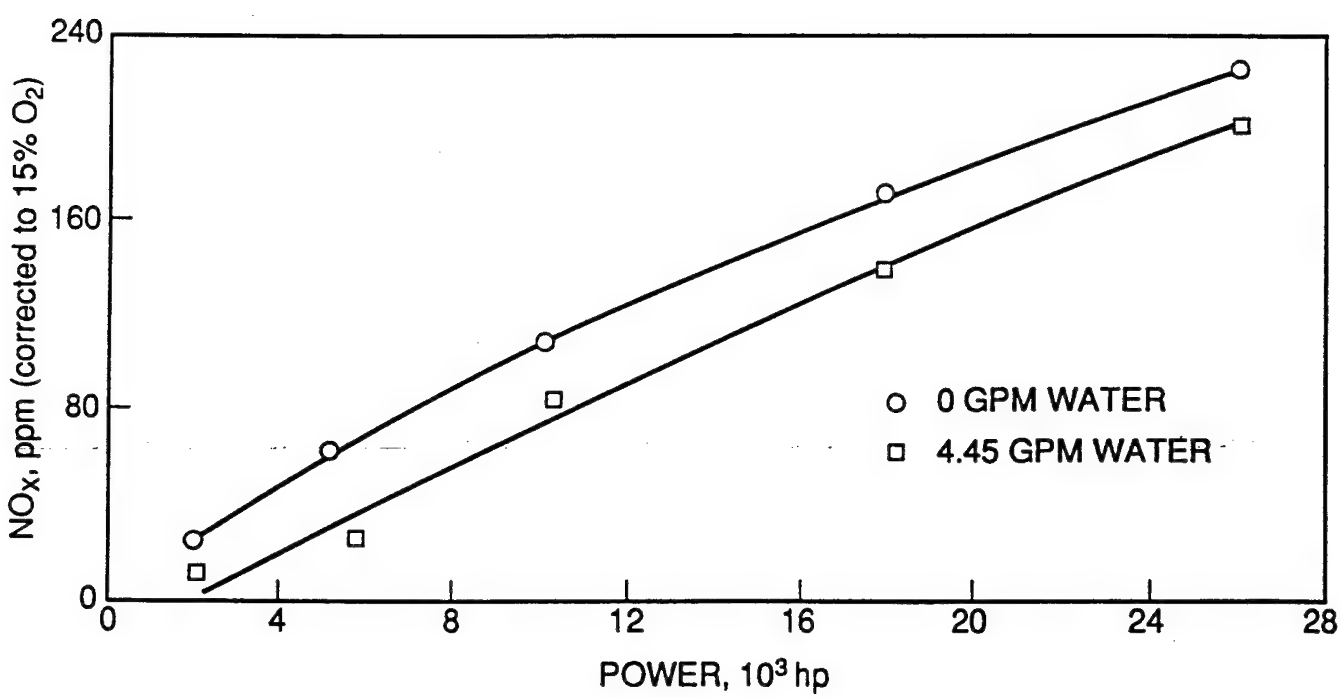

Figure 5. The effect of WFI on the compressor discharge temperature of the LM2500 gas turbine.

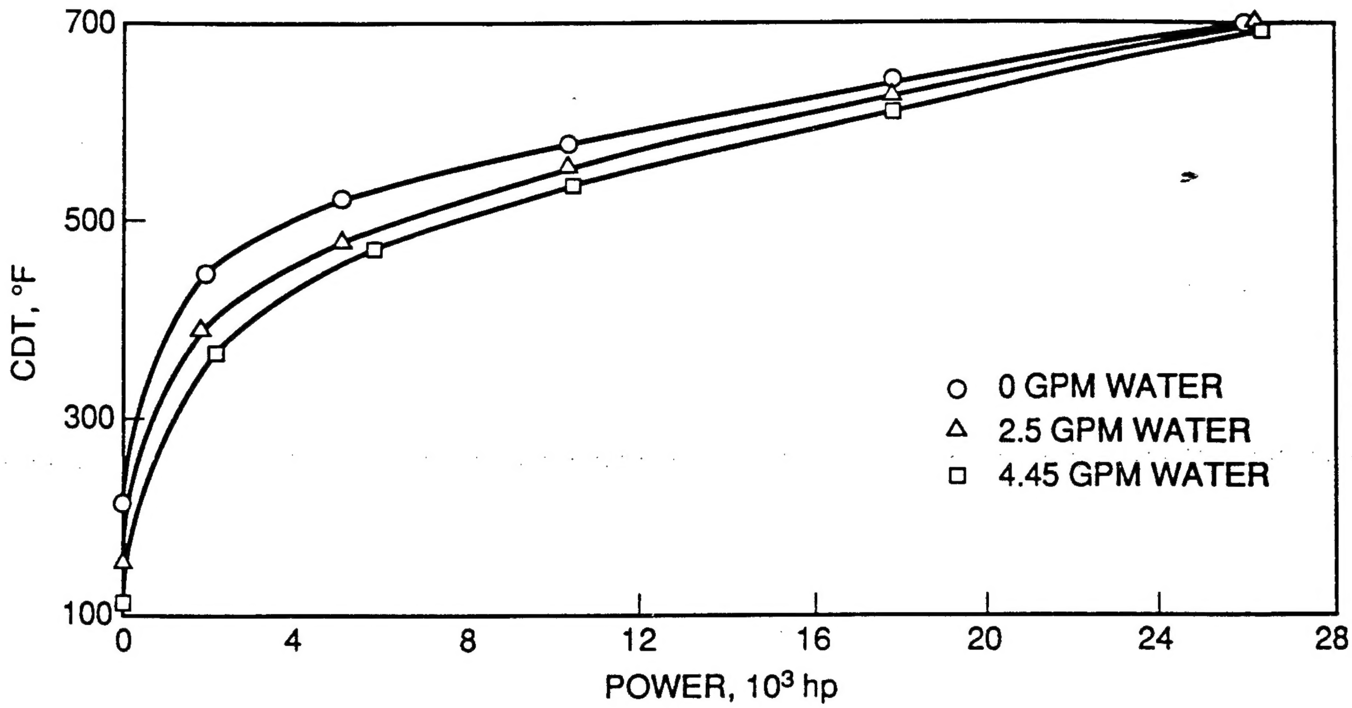

Figure 6. The effect of WFI on the free-power-turbine inlet temperature of the LM2500 gas turbine.

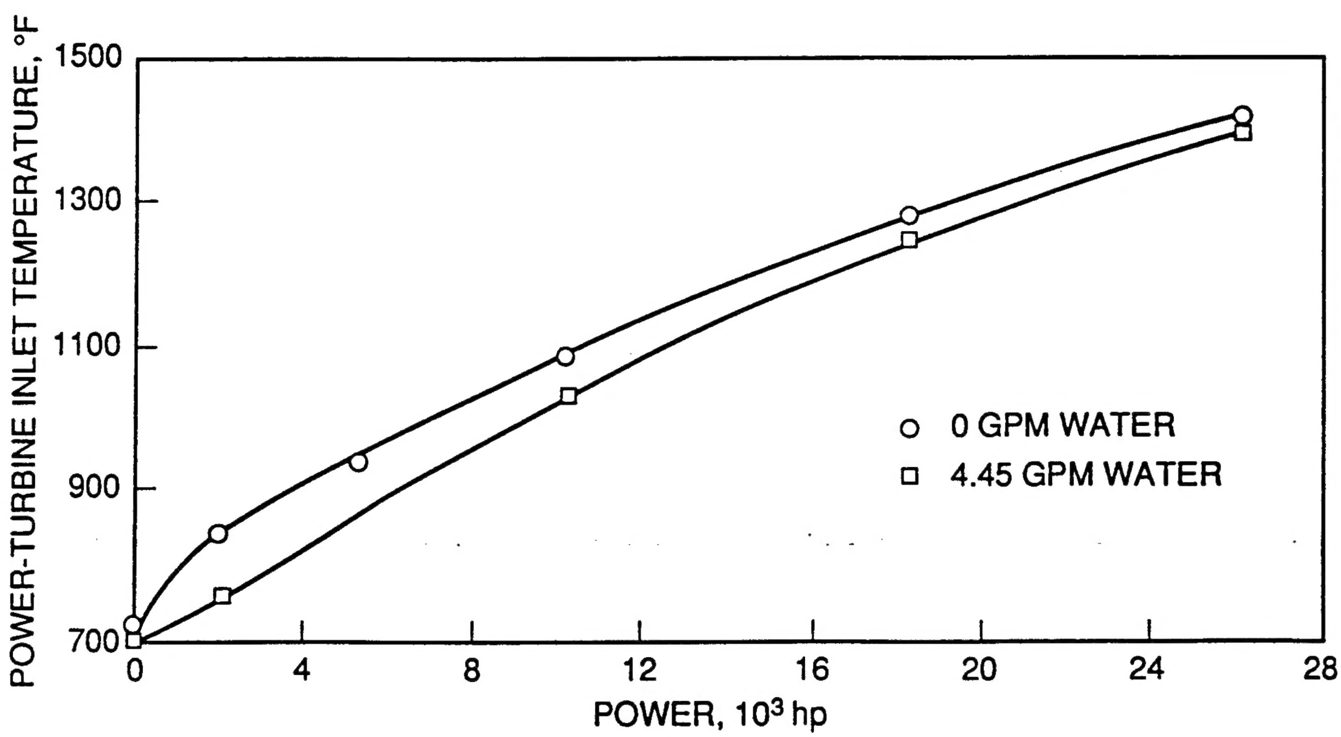

Figure 7. The effect of WFI on the specific fuel consumption of the LM2500 gas turbine.

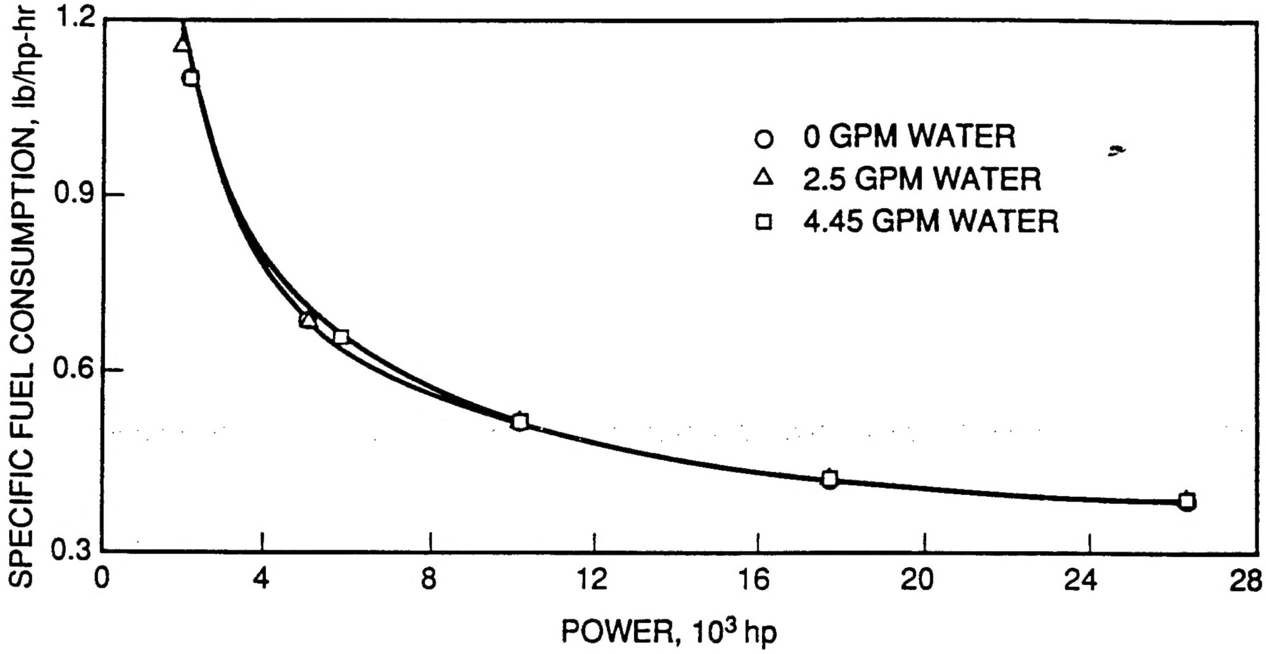

Figure 8. Schematic of a simple-cycle gas turbine with WFI.

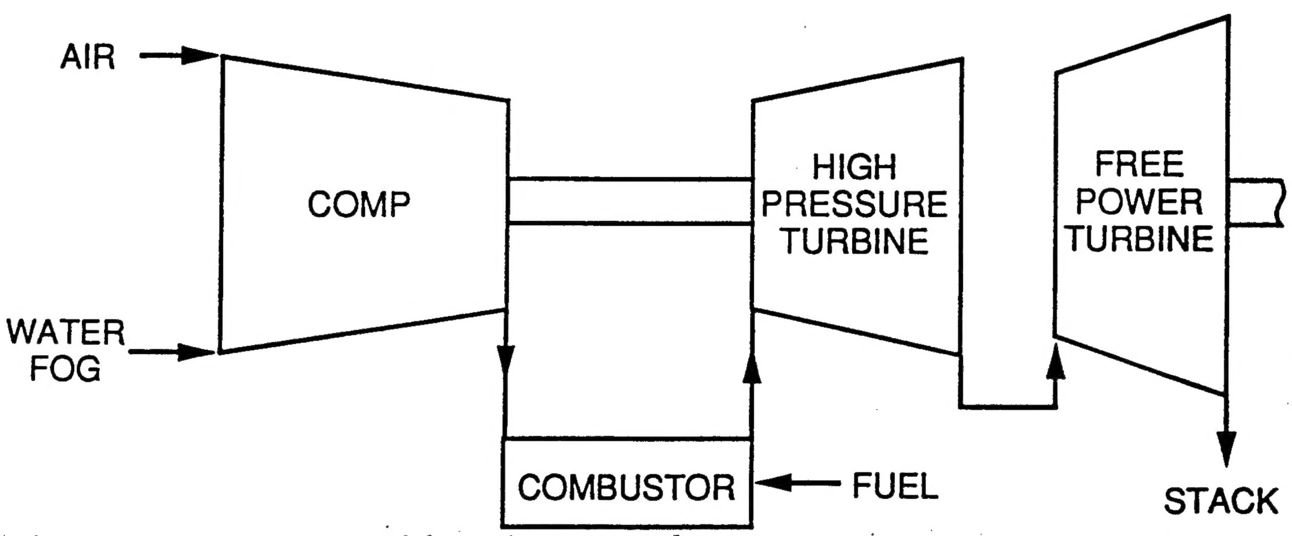

Figure 9. The effect of varying WFI flow rates on the performance of the simple-cycle gas turbine.

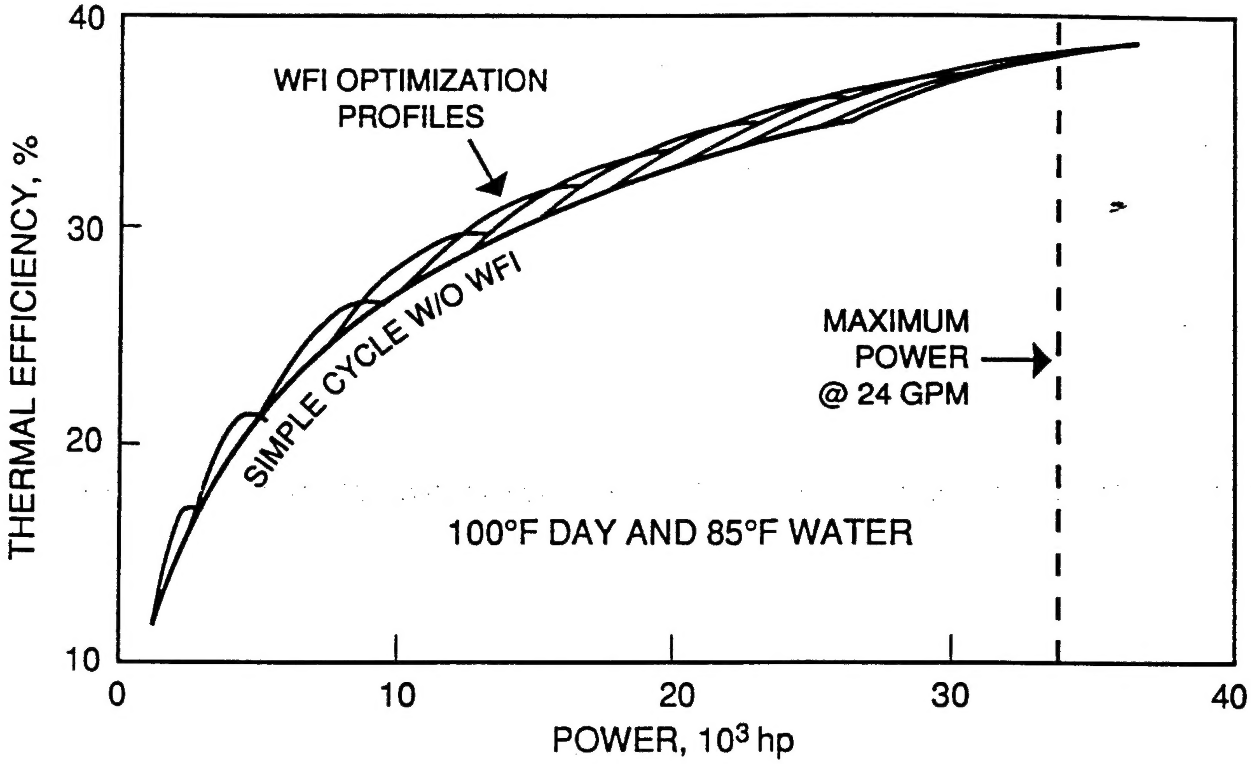

Figure 10. The effect of a fixed WFI rate on the performance of a simple-cycle gas turbine.

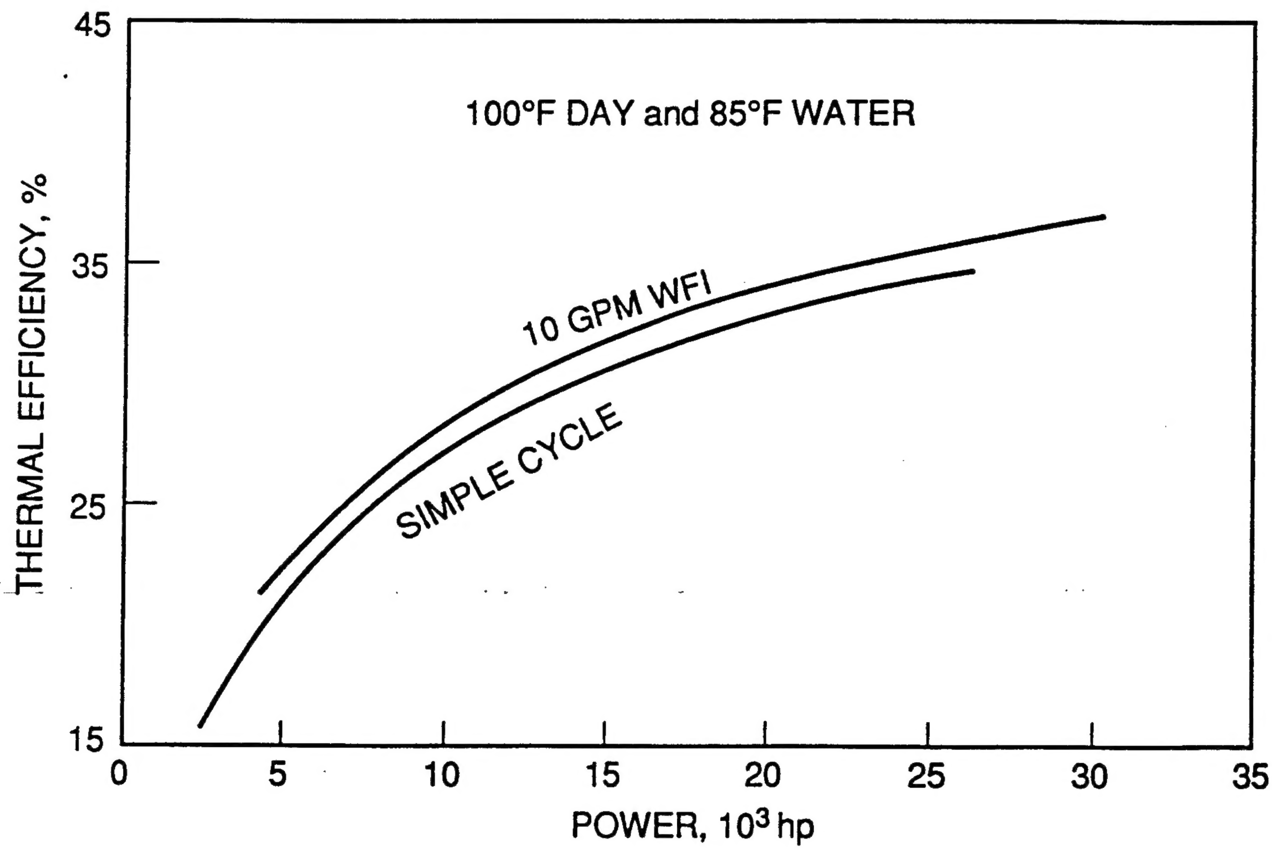

Figure 11. Schematic of a recuperated gas turbine with WFI.

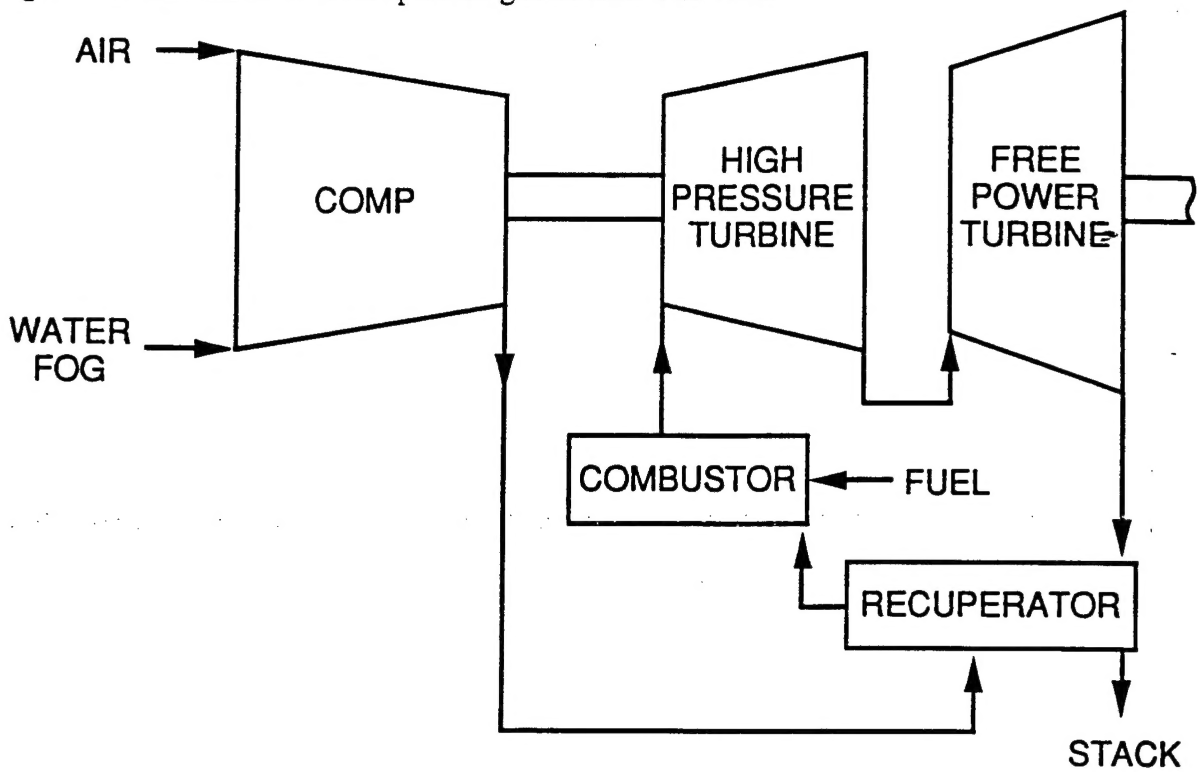

Figure 12. Comparison of cycle options with WFI.